Table 3

New Look-Up Table

Digital Value	Linear Gray Scale Density	Bands 1, 2, 3, 4, 5, 7 Density	Band 6 Density
0	2.20	2.30	2.20
16	2.07	1.67	2.20
34	1.93	1.43	2.16
50	1.80	1.26	2.01
68	1.67	1.10	1.76
84	1.53	0.97	1.50
102	1.40	0.85	1.20
118	1.27	0.75	0.95
136	1.13	0.65	0.70
152	1.00	0.57	0.49
170	0.87	0.49	0.32
186	0.73	0.43	0.24
204	0.60	0.37	0.22
220	0.47	0.33	0.20
238	0.33	0.28	0.20
255	0.20	0.24	0.20

solved using these values the new tables will be implemented on September 1, 1986. Imagery requested after that date will be processed through the new transformations.

Landsat MSS and TM Post-Calibration Dynamic Ranges, Exoatmospheric Reflectances and At-Satellite Temperatures

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The purpose of this paper is to provide users of Landsat digital images of the Earth with equations and constants for convertng from numbers on tapes to scientific units such as radiance. Constants are tabulated for all the MSS (Multispectral Scanner) and TM (Thematic Mapper) sensors that have been put in orbit. Quantized and calibrated values for individual pixels on radiometrically and geometrically calibrated computer compatible tapes (CCT-P) are given the symbol "QCAL". These post-calibration QCAL values are in units of digital numbers (DN), which have a full range of 6, 7 or 8 bits. Specific constants are given for converting QCAL values to spectral radiance (L_λ), in-band radiance (L), and either exoatmospheric reflectance (ρ) or at-satellite temperatures (T), where λ is used as a subscript to indicate "spectral" rather than "in-band" units. These conversions provide a basis for more normalized comparison of data in single scenes, or between images taken on different dates and/or by different sensors.

MSS and TM Dynamic Range:

Radiometric calibration of both the MSS and TM scanners is accomplished by rescaling the raw digital data transmitted from the satellite to calibrated digital data, which have the same post-calibration dynamic range for all scenes processed on the ground for a specific period of time. The absolute radiometric calibration between bands on both sensors is maintained by using internal calibrators (IC) which are physically located between the telescope and the detectors and are sampled at the end of a scan (for MSS, see Alford and Barker, 1983; for TM, see Barker, Abrams, et al., 1985a). Relative within-band radiometric calibration, to reduce "striping", is provided by a scene-based procedure called histogram equalization. The absolute accuracy and relative precision of this calibration scheme assumes that any change in the optics of the primary telescope or the "effective irradiance" from the IC lamps are insignificant in comparison to the changes in detector sensitivity and electronic gain and bias with time and that the scene-dependent sampling is sufficiently precise for the required within-scan destriping from histogram equalization. Each MSS and TM reflective band and the IC lamps were calibrated prior to launch using lamps in integrating spheres which were in turn calibrated against lamps traceable to calibrated NBS lamps (Barker, Ball, et al., 1984; Barker, Ball, et al., 1985). Sometimes the absolute radiometric calibration constants in the "short-term" and "long-term parameters" files used for ground processing have been modified after launch either because of inconsistency within or between bands, changes in the inherent dynamic range of the sensors or desires to make QCAL values from one sensor match those from another.

Conversion from calibrated QCAL values on user-purchased CCT-P tapes to spectral radiance, L_λ, is accomplished with the following equation by knowing the lower and upper limit of the post-calibration dynamic range for a specific band, namely $LMIN_\lambda$ and $LMAX_\lambda$:

$$L_\lambda = LMIN_\lambda + \left(\frac{LMAX_\lambda - LMIN_\lambda}{QCALMAX}\right) QCAL \qquad (1)$$

where

- QCAL = Calibrated and quantized scaled radiance in units of DN, digital numbers
- $LMIN_\lambda$ = Spectral radiance at QCAL = 0
- $LMAX_\lambda$ = Spectral radiance at QCAL = QCALMAX
- QCALMAX = Range of rescaled radiance in DN
- L_λ = Spectral radiance

Tables 1 and 2 provide the band-specific $LMIN_\lambda$ and $LMAX_\lambda$ parameters that have been used at different times and by different systems for the ground processing of MSS and TM data at NASA's Goddard Space Flight Center (GSFC). Units of spectral radiance in these tables are milliwatts per square centimeter per steradian per micrometer ($mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$). Maximum QCAL values after calibration, QCALMAX, are 255 DN for all TM data, and 127 DN for all MSS data except Band 4 (0.8-1.1 μm) for certain time periods. Band 4 MSS data for Landsat 1-3 acquired before February 1, 1979 (X-format CCT's) and Landsat-4 MSS data processed before October 22, 1982 used QCALMAX = 63 DN.

For spectral radiances, an identical post-calibration dynamic range has been provided for each band in the TM sensor on both Landsat-4 and -5, even though the relative spectral response functions are not identical on the two sensors (Barker, 1984 (Table 1) and Barker, 1985 (Table 1-1, and Appendix 9.1)). In general, spectral radiance is a

Table 1

MSS Post-Calibration Dynamic Ranges for U.S. Processed Data

Spectral Radiances, $LMIN_\lambda$ and $LMAX_\lambda$, in $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$ a

Satellite Applicable Dates[b]	MSS 1 (was MSS 4) $LMIN_\lambda$	$LMAX_\lambda$	MSS 2 (was MSS 5) $LMIN_\lambda$	$LMAX_\lambda$	MSS 3 (was MSS 6) $LMIN_\lambda$	$LMAX_\lambda$	MSS 4 (was MSS 7) $LMIN_\lambda$	$LMAX_\lambda$
Landsat-1								
ALL	0.0	24.8	0.0	20.0	0.0	17.6	0.0	15.3[e]
Landsat-2								
<7/16/75	1.0	21.0	0.7	15.6	0.7	14.0	0.5	13.8
≥7/16/75	0.8	26.3	0.6	17.6	0.6	15.2	0.4	13.0
Landsat-3								
<6/1/78	0.4	22.0	0.3	17.5	0.3	14.5	0.1	14.7
≥6/1/78[c]	0.4	25.9	0.3	17.9	0.3	14.9	0.1	12.8
Landsat-4								
<8/26/82[d]	0.2	25.0	0.4	18.0	0.4	15.0	0.3	13.3
8/26/82-3/31/83	0.2	23.0	0.4	18.0	0.4	13.0	0.3	13.3
≥4/1/83	0.4	23.8	0.4	16.4	0.5	14.2	0.4	11.6
Landsat-5								
<4/6/84[d]	0.4	24.0	0.3	17.0	0.4	15.0	0.2	12.7
4/6/84-11/8/84	0.3	26.8	0.3	17.9	0.4	15.9	0.3	12.3
≥11/9/84	0.3	26.8	0.3	17.9	0.5	14.8	0.3	12.3

a Landsat-1/2/3 data derived from GE (1978) as corrected by Grebowsky (1985). Landsat-4/5 data derived from pre-launch calibration data and post-launch modifiers in MIPS (MS Image Processing System at Goddard) short term parameter files (Cantril, 1985)

b Landsat-1/2/3 dates are processing dates; Landsat-4/5 are acquisition dates at 0000 GMT

c Some data acquired as early as 4/24/78 were processed with these parameters

d Preproduction periods - limited data available.

e Landsat-1, Band 4 data were not calibrated post-launch using the IC, this number is per specifications; this value has been frequently reported as 13.3 (in-band radiance of 4.00 $mW \bullet cm^{-2} \bullet ster^{-1}$) apparently due to an error in the Landsat Data Users Handbook, which was subsequently noted in an ERRATA sheet

Table 2

TM Post-Calibration Dynamic Ranges for U.S. Processed Data

Spectral Radiances, $LMIN_\lambda$ and $LMAX_\lambda$, in $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$

Band	Prior to August 1983 (Scrounge-ERA processing)[a] $LMIN_\lambda$	$LMAX_\lambda$	Prior to 15 Jan 1984 (TIPS-ERA processing)[b] $LMIN_\lambda$	$LMAX_\lambda$	After 15 Jan 1984 (TIPS-ERA processing)[c] $LMIN_\lambda$	$LMAX_\lambda$
TM 1	-0.152	15.842	0.000	14.286	-0.15	15.21
TM 2	-0.284	30.817	0.000	29.125	-0.28	29.68
TM 3	-0.117	23.463	0.000	22.500	-0.12	20.43
TM 4	-0.151	22.432	0.000	21.429	-0.15	20.62
TM 5	-0.037	3.242	0.000	3.000	-0.037	2.719
TM 6	0.20	1.564	0.484	1.240	0.1238	1.5600
TM 7	-0.015	1.700	0.000	1.593	-0.015	1.438

a Barker, Ball et al., 1984 (Table 3)

b Very little data were processed with these parameters because only small amounts of TM data were being collected at this time, e.g., TIPS "Long Term Parameter File" number TL4888.PAR was generated on 20 July 1983

c Barker, 1984 (Table 1), and Barker, 1985 (Table 1-1 and Appendix 9), as carried in TIPS (TM Image Processing System at Goddard) Long Term Parameter File Number TL5027.PAR for in-band radiance from full-width half maximum band-width for Landsat-5 and generated on 23 August 1984

Table 3

MSS Mean Solar Exoatmospheric Spectral Irradiances

$ESUN_\lambda$ ($mW \bullet cm^{-2} \bullet \mu m^{-1}$) a,b

Satellite \ Band	MSS 1 (was MSS 4)	MSS 2 (was MSS 5)	MSS 3 (was MSS 6)	MSS 4 (was MSS 7)
LANDSAT-1	185.2 ±0.8	158.4 ±0.6	127.6 ±0.4	90.4 ±0.5
LANDSAT-2	185.6 ±0.1	155.9 ±0.4	126.9 ±0.6	90.6 ±0.3
LANDSAT-3	186.0 ±0.3	157.1 ±0.6	128.9 ±0.5	91.0 ±0.6
LANDSAT-4	185.1 ±0.2	159.3 ±0.7	126.0 ±0.3	87.8 ±1.0
LANDSAT-5	184.9 ±0.2	159.5 ±0.3	125.3 ±0.1	87.0 ±0.7
MEAN and STD. DEV.c	185.4 ±0.4	158.0 ±1.5	126.9 ±1.4	89.4 ±1.8

a Solar Data from Neckel and Labs, 1984

b Standard deviations of six channels within a band

c Standard deviations of five MSS sensors for a specified band useful variable for comparing data from sensors which have similar bands.

Equations for using spectral bandwidths to calculate "in-band radiance" rather than "spectral radiance" are contained in Appendix 1. Appendix 2 gives the dynamic range information contained on each CCT-PT tape, which can be used to verify constants, if there are changes in the future.

MSS and TM Exoatmospheric Reflectance:

For relatively clear Landsat scenes, a reduction in between-scene variability can be achieved through a normalization for solar irradiance by converting spectral radiance calculated in Equation 1 to effective at-satellite reflectance, or in-band planetary albedo. This combined surface and atmospheric reflectance of the Earth is given by:

$$\rho_p = \frac{\pi \bullet L_\lambda \bullet d^2}{ESUN_\lambda \bullet \cos\theta_s} \tag{2}$$

where

ρ_p = Unitless effective at-satellite planetary reflectance

L_λ = Spectral radiance at sensor aperture in $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$ from Eq. 1

d = Earth-Sun distance in astronomical units from nautical handbook

$ESUN_\lambda$ = Mean solar exoatmospheric irradiances in $mW \bullet cm^{-2} \bullet \mu m^{-1}$ from Tables 3 (MSS) and 4 (TM)

θ_s = Solar zenith angle in degrees

Table 4

TM Solar Exoatmospheric Spectral Irradiances

$ESUN_\lambda$ ($mW \bullet cm^{-2} \bullet \mu m^{-1}$) a,b

Band \ Satellite	Landsat-4	Landsat-5
TM 1	195.8	195.7
TM 2	182.8	182.9
TM 3	155.9	155.7
TM 4	104.5	104.7
TM 5	21.91	21.93
TM 7	7.457	7.452

a Solar data from Neckel and Labs, 1984 (Bands 1-4) and from Iqbal, 1983 (Band 5 and Band 7)
b Up-dated from Markham and Barker, 1985 (Table 11)

TM Band 6 At-Satellite Temperatures:

TM Band 6 imagery can also be converted from spectral radiance (Equation 1) to a more physically useful variable, namely the effective at-satellite temperatures of the viewed Earth-atmosphere system under an assumption of unity emissivity and using pre-launch calibration constants in Table 5 (up-dated from Lansing and Barker, 1985, Table 1):

$$T = \frac{K2}{\ln\left(\frac{K1}{L_\lambda} + 1\right)} \tag{3}$$

where

T = Effective at-satellite temperatures in Kelvin, K

K2 = Calibration constant 2 in K from Table 5

K1 = Calibration constant 1 in $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$ from Table 5

L_λ = Spectral radiance in $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$ from Eq. 1

Table 5

Landsat TM Thermal Band Calibration Constants

Satellite	Constant 1 K1 (K)	Constant 2 K2 ($mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$)
Landsat-4	67.162	1284.3
Landsat-5	60.776	1260.56

Discussion of Radiometric Accuracy:

Assessment of accuracy of these absolute radiometric constants is difficult at present. The uncertainties in pre-launch and post-launch up-dates of the absolute radiometric calibration constants (Tables 1 and 2) are nominally specified to be less than 10%. An rms summing of known errors in the pre-launch calibration suggests that this may be a reasonable estimate of overall uncertainty in the pre-launch calibration (for TM, see Barker, Ball et al, 1985 [Figure 5]). There is some evidence for uncalibrated sensor-dependent changes in the external MSS optics with time (Nelson, 1985). There are also known, but as yet uncorrected, effects associated with temperature-dependence of the TM internal calibrator that may be contributing to apparent discontinuous changes at launch (Barker, Abrams, et al., 1985a and 1985b) and to the continuous changes of gain while in orbit (Barker, 1985, Fig. 2-1 and 2-2). Additional uncertainties for exoatmospheric reflectances are probably less than 2% in the visible/near-infrared and less than 5% in the short-wave infrared (SWIR) portion of the spectrum as judged by the current differences in estimates of the solar irradiance. The reproducibility of ground measurements at White Sands, NM, at times of TM overpass to about 5% for 5 dates for Bands 1-4 is suggesting a potential for monitoring sensor change for the whole system with time (Slater, 1986).

Conclusions

This paper provides a method of converting digital numbers on calibrated CCT-P tapes into scientifically meaningful variables for the MSS and TM sensors on the Landsat satellites. Equations 1, 2 and 3 and the associated Tables 1, 2, 3, 4 and 5, are the recommended ones for implementing these conversions.

Appendices

Appendix 1: MSS and TM Spectral Bands

An alternative variable to use in converting from calibrated digital values of rescaled radiance, QCAL(DN), to radiance, is integrated in-band radiance, L, rather than spectral radiance, L_λ as given in the following equation:

$$L = BW \bullet L_\lambda \quad (4)$$

where

L = In-band radiance for a pixel in a specific band

BW = Band-width of that band; defined as the difference between the upper and lower band edges of the band-pass

L_λ = Spectral radiance for the pixel in that band

Pre-launch calibration of both MSS and TM was effectively done in spectral radiances. Three types of band-widths, BW, have been used to convert from spectral to in-band radiance. The most commonly used conversion is the specified "nominal" band-width, BW_n, i.e. as defined in the original specifications for the sensor:

$$L_n = BW_n \bullet L_\lambda \quad (5)$$

where

L_λ = Spectral radiance in $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$

BW_n = Nominal band-width in μm

L_n = In-band radiance in $mW \bullet cm^{-2} \bullet ster^{-1}$

The MSS dynamic range has been generally presented in the literature as $LMIN_n$ and $LMAX_n$ (historically called RMIN and RMAX) using BW_n values of 0.1, 0.1, 0.1 and 0.3 μm for Bands 1, 2, 3 and 4, respectively (e.g., Robinove, 1982). Band-widths for sensors on Landsat, which were derived from measured relative spectral response curves, RSR, have usually been represented as a full-width at half maximum, BW_f, or as quadratic moment band-width, BW_q, as recommended by Palmer (1984) to capture some of the variability in the observed RSR. The corresponding in-band radiances are:

$$L_f = BW_f \bullet L_\lambda \quad (6)$$

and

$$L_q = BW_q \bullet L_\lambda \quad (7)$$

where

L_λ = Spectral radiance in $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$

BW_f = Observed band-width as full-width at half maximum in μm

BW_q = Calculated band-width by the Quadratic Moment Method in μm

L_f = In-band radiance using a band-width of full-width at half maximum in $mW \bullet cm^{-2} \bullet ster^{-1}$

L_q = In-band radiance using a band-width calculated by the Quadratic Moment Method in $mW \bullet cm^{-2} \bullet ster^{-1}$

Tables 6 and 7 provide a summary of the band-widths for MSS and TM scanners, respectively. If required, equations 1 and 5-7 can be used to calculate in-band radiances from the parameters in Tables 1, 2, 6 and 7.

Appendix 2: TM CCT-PT Dynamic Range Constants

There have been occasional changes in the post-calibration dynamic range, even for a specific sensor, as indicated in Tables 1 and 2. There will probably be some changes in the future, especially in TM data, as the observed in-orbit imagery is examined and found to require less expansion during calibration and/or possible adjustment of the calibration constants based on comparisons to absolute radiometric measurements made on the ground. In any case, the data on CCT-PT tapes that have been prepared in the past, and will be prepared in the future, contain the dynamic range used at the time of linear calibration of that scene.

Information about the actual post-calibration dynamic range that was used for each band can be obtained from two different files on CCT-PT tapes. One file is the "Supplemental Data File", namely file number 24, before the "Null Volume File" at the end of the tape for each quadrant of the scene. Records 2-8, which are entitled "Band Quality Data Records" *(EOSAT, 1985, Table 5-21)*, of this "Supplemental Data File" contain the minimum and maximum values of the dynamic range for Bands 1-7 at respective locations of bytes 41-44 and bytes 45-48 and are written in single-precision floating-point DEC-VAX compatible format (Real*4). For the six reflective bands, the minimum in-band radiance at QCAL = 0 DN and the maximum at QCAL = 255 DN for a specific band are given, as special cases of Equation 6, by:

Table 6

Landsat MSS Spectral Bands

Band	MSS 1 (was MSS 4)		MSS 2 (was MSS 5)		MSS 3 (was MSS 6)		MSS 4 (was MSS 7)	
	Band-Pass (μm)	Band-Width (nm)	Band-Pass (μm)	Band-Width (nm)	Band-Pass (μm)	Band-Width (nm)	Band-Pass (μm)	Band-Width (nm)
"Nominal" Specification	.5 .6	100	.6 .7	100	.7 .8	100	.8 1.1	300
Landsat-1[a]	.4968 .6050	108.2	.5988 .7068	108.0	.6885 .8086	120.1	.7909 1.0326	241.7
Landsat-2[a]	.4943 .6027	108.5	.6036 .7164	112.8	.6909 .8108	119.9	.7896 1.0323	242.8
Landsat-3[a]	.4939 .5991	105.1	.6026 .7105	107.9	.6872 .8003	113.1	.7966 1.0185	221.8
Landsat-4[a]	.4921 .6094	117.3	.5998 .7006	100.9	.6954 .8129	117.5	.7903 1.0637	273.5
Landsat-5[a]	.4947 .6109	116.2	.6001 .6990	98.8	.6985 .8148	116.3	.7937 1.0690	275.2

a Band-Pass and Band-Width calculated here by quadratic moment method of Palmer

Table 7

Landsat TM Spectral Bands

BAND	Nominal Specifications[a]		Full-Width at Half Maximum				Quadratic Moment[b]			
	Band-Pass Lower-Upper	Band-Width BW_n	Band-Pass[b] Lower-Upper		Band-Width[c] BW_f		Band-Pass Lower-Upper		Band-Width BW_q	
			L-4	L-5	L-4	L-5	L-4	L-5	L-4	L-5
	(μm)	(nm)	(μm)	(μm)	(nm)	(nm)	(μm)	(μm)	(nm)	(nm)
TM 1	.45 .52	70	.4518 .5180	.4524 .5178	66	66	.4503 .5218	.4512 .5214	71.5	70.1
TM 2	.52 .60	80	.5288 .6094	.5280 .6093	81	82	.5269 .6156	.5262 .6150	88.7	88.9
TM 3	.63 .69	60	.6244 .6930	.6264 .6932	69	67	.6213 .6984	.6223 .6989	77.1	76.6
TM 4	.76 .90	140	.7760 .9051	.7764 .9045	129	128	.7719 .9068	.7710 .9053	134.9	134.3
TM 5	1.55 1.75	200	1.5676 1.7845	1.5675 1.7842	216	217	1.5640 1.7911	1.5640 1.7904	227.1	226.5
TM 7	2.08 2.35	270	2.0972 2.3474	2.0972 2.3490	250	252	2082.4 2351.2	2.0831 2.3513	268.8	268.2

a *Engel, 1980; and Engel and Weinstein, 1983; Salomonson et al., 1980*
b *Markham and Barker, 1985 (Table 10)*
c *Barker, 1985 (Appendix 9.1); rounded numbers used by TIPS*

$$LMIN_f = BW_f \bullet LMIN_\lambda \qquad (8)$$

where

- $LMIN_f$ = Minimum in-band radiance at QCAL = 0 DN using a band-width of full-width at half maximum
- BW_f = Observed spectral band-width as full-width at half maximum *(see Table 7)*
- $LMIN_\lambda$ = Minimum spectral radiance at QCAL = 0 DN *(see Table 2)*

and

$$LMAX_f = BW_f \bullet LMAX_\lambda \qquad (9)$$

where

- $LMAX_f$ = Maximum in-band radiance at QCAL = 255 DN using a band-width of full-width at half maximum
- BW_f = Spectral band-width *(see Table 7)*
- $LMIN_\lambda$ = Maximum spectral radiance at QCAL = 255 DN *(see* Table 2)

For the TM thermal band, the dynamic range is in the same spectral radiance units as in Table 2. The second location of dynamic range information on CCT-PT tapes is in bytes 29-48 and 49-68 (IBM E20.10 format) of the "Radiometric Calibration Ancillary Record" for each band in the "Leader File" at the beginning of each tape *(EOSAT, 1985, Table 5-16)*. These calibration constants are in the form of an offset and a gain for converting a QCAL value for a specific pixel from units of DN to spectral radiance for each band:

$$L_\lambda = AO_\lambda + A1_\lambda \bullet QCAL \qquad (10)$$

where

- L_λ = Spectral radiance for a specific pixel in units of $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$
- AO_λ = Post-calibration offset constant in units of $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1}$
- $A1_\lambda$ = Post-calibration gain coefficient in units of $mW \bullet cm^{-2} \bullet ster^{-1} \bullet \mu m^{-1} \bullet DN^{-1}$
- QCAL = Quantized and calibrated scaled radiance of a specified pixel in units of DN

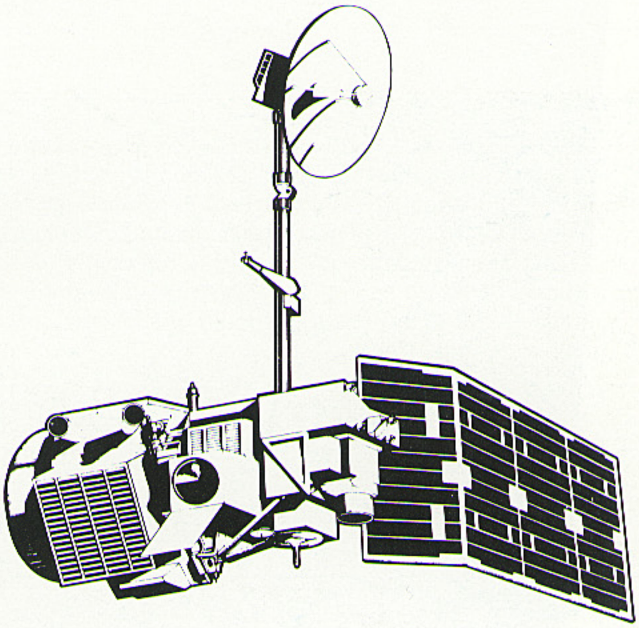
and from Equation 1:

$$AO_\lambda = LMIN_\lambda \qquad (11)$$

and

$$A1_\lambda = (LMAX_\lambda - LMIN_\lambda)/255 \qquad (12)$$

Some of the earlier documentation on CCT formats has contained wrong byte location and wrong units for the constants in Equations 8, 9 and 10. The method of preparing the tapes, however, has remained the same and is correctly documented in the current User's Guide *(EOSAT, 1985)*.



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